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Zonal wave numbers of the summertime 2 day planetary wave observed in the mesosphere by EOS Aura Microwave Limb Sounder

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[1] Recent observations and theoretical work suggest that the 2 day planetary wave in the summertime mesosphere is composed of multiple superposed zonal wave numbers. Here we use EOS Aura Microwave Limb Sounder (MLS) temperature data to determine the component zonal wave numbers of the 2 day wave in the mesosphere at latitudes of 70°S to 70°N from 2004 to 2009. We consider the effect of aliasing between different wave numbers and note that significant aliasing can occur and result in spurious signals, particularly at high latitudes in winter. The seasonal evolution of the different wave numbers is investigated and found to be very different between the Northern and Southern Hemispheres. In both hemispheres the wave is dominated by westward traveling waves of zonal wave number 3 and 4 (W3 and W4). However, in the Southern Hemisphere the wave is dominated by the W3 component, but in the Northern Hemisphere the W3 component is smaller and the W4 component is often of similar or larger amplitude. A small-amplitude westward traveling zonal wave number 2 (W2) wave is also evident in both hemispheres. In the Northern Hemisphere, the W2 amplitudes never exceed 3 K, the W3 amplitudes can reach 3.5 K, and the W4 can be the largest component, reaching amplitudes of 4 K. In the Southern Hemisphere, the W2 amplitudes can reach up to 3.5 K, the W3 amplitudes can be much larger, reaching 12 K, and the W4 amplitudes are smaller than in the Northern Hemisphere, in 4 out of 5 years not exceeding 3 K. The Northern Hemisphere W4 can reach large amplitudes in August when the W3 is small, which means that the late summer Northern Hemisphere quasi-2 day wave is usually a W4 oscillation rather than the familiar W3. In contrast, in the Southern Hemisphere, the W3 is often larger than the W4 around the summer solstice, and there are no episodes observed where the wave becomes dominated by the W4 for an extended period of time. A high degree of interannual variability is evident, particularly in the Southern Hemisphere, where the W3 peak amplitudes vary from 12 K in January 2006 to 3 K in January 2009. The height-latitude structure of the W4 suggests that this wave is a (4, 0) Rossby-gravity wave.

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1. Introduction

[2] The 2 day planetary wave is one of the most important features in the dynamics of the summertime middle atmosphere. At its maximum it is the largest amplitude planetary wave observed anywhere in the mesosphere, as large as 11 K in the Southern Hemisphere [e.g., *Limpasuvan and Wu*, 2003]. The wave is usually observed for about one to two months after the summer solstice when it is present from the upper stratosphere to the lower thermosphere. Wave temperature-amplitudes maximize at midlatitudes and at heights near the mesopause, and the wave is present from equatorial to polar latitudes. Wave amplitudes are known to be larger in the Southern Hemisphere than the Northern Hemisphere and the wave is primarily a westward propagating feature of zonal wave number 3, although other wave numbers have been observed.

[3] The 2 day wave is important in the dynamics of the middle atmosphere because it is known to strongly interact with atmospheric tides and to modulate their amplitude [e.g., *Teitelbaum and Vial*, 1991; *Mitchell et al.*, 1996; *Palo et al.*, 1999; *Pancheva et al.*, 2004; *Wu et al.*, 2008]. Further, there is evidence that the 2 day wave can become phase locked to the migrating semidiurnal and diurnal tides (i.e., have a period of exactly 48 h) and through interaction

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with them generate a diurnal zonal wave number 6 feature and lead to rapid amplification of the 2 day wave amplitude [e.g., *Walterscheid and Vincent*, 1996; *Hecht et al.*, 2010; *McCormack et al.*, 2010]. Interactions with tides can also act to constrain 2 day wave amplitudes and results in a cascade of variance to smaller scales within the atmosphere [*Salby and Callaghan*, 2008]. The 2 day wave influences the photochemistry and transport of minor species in the mesosphere [e.g., *Kulikov*, 2007]. Nonlinear coupling between the 2 day wave and the migrating diurnal tide has been proposed as a mechanism capable of exciting other planetary wave modes (e.g., eastward wave number 2 [*Palo et al.*, 2007]). The temperature perturbations associated with the wave have been shown to control the variability of polar mesospheric clouds [e.g., *Merkel et al.*, 2009]. Evidence that the 2 day wave at low latitudes influences polar summer time mesopause region temperatures by up to as much as 9 K has been provided by *Morris et al.* [2009] based on the occurrence frequency of polar mesosphere summer echoes. The 2 day wave is also known to produce a strong modulation of the ionosphere through mechanisms which remain poorly understood [e.g., *Forbes et al.*, 1997; *Forbes and Zhang*, 1997], these in turn produce a 2 day modulation of the geomagnetic field [*Yamada*, 2009]. There are also suggestions that the equatorial quasi-biennial oscillation (QBO) influences the amplitude of the 2 day wave [*Li et al.*, 2008].

[4] The 2 day wave was first detected in meteor radar observations of mesospheric winds by *Muller* [1972]. The wave has since been extensively studied by ground-based radar and satellites. Meteor and MF radars were first used to investigate the structure and climatology of the wave in wind perturbations. The majority of ground-based studies have been made at middle and low latitudes [e.g., *Salby and Roper*, 1980; *Craig et al.*, 1983; *Plumb et al.*, 1987; *Tsuda et al.*, 1988; *Harris and Vincent*, 1993; *Palo and Avery*, 1996; *Jacobi et al.*, 1997; *Thayaparan et al.*, 1997; *Jacobi et al.*, 1998; *Gurubaran et al.*, 2001; *Manson et al.*, 2004a; *Pancheva et al.*, 2004; *Riggin et al.*, 2004; *Meek and Manson*, 2009]. There have been comparatively few ground-based studies of the wave at polar latitudes [e.g., *Nozawa et al.*, 2003a, 2003b; *Manson et al.*, 2004b; *Merzlyakov et al.*, 2004; *Riggin et al.*, 2004; *Nozawa et al.*, 2005; *Palo et al.*, 2007; *Baumgaertner et al.*, 2008; *Sandford et al.*, 2008; *Tunbridge and Mitchell*, 2009]. These ground-based radar observations have led to a general overall understanding of the characteristics of the 2 day wave, including its vertical structure, period wind amplitudes and seasonal variability.

[5] However, ground-based radar measurements are limited to a particular latitude and longitude making it not possible for a single instrument to determine the zonal structure of the wave, i.e., to determine the zonal wave number. To overcome this limitation, some studies have been conducted using longitudinally spaced networks of two or more ground-based radars [e.g., *Glass et al.*, 1975; *Muller and Nelson*, 1978; *Clark et al.*, 1994; *Pancheva et al.*, 2004]. However, they were limited by instrument biases and spatial ambiguities due to sparse sampling which is not necessarily present in satellite observations.

[6] Satellite observations of the 2 day wave have been made using various instruments that measure atmospheric temperature including the Nimbus 5 SCR and Nimbus 6 PMR [e.g., *Rodgers and Prata*, 1981], Microwave Limb Sounder (MLS) on UARS [e.g., *Limpasuvan and Wu*, 2003; *Riggin et al.*, 2004] SABER on TIMED, [e.g., *Garcia et al.*, 2005; *Palo et al.*, 2007] and EOS MLS on Aura [e.g., *Limpasuvan et al.*, 2005; *Sandford et al.*, 2008; *Meek and Manson*, 2009]. Satellite instruments have also been used to measure atmospheric wind values of the 2 day wave, e.g., HRDI on UARS [e.g., *Wu et al.*, 1993; *Riggin et al.*, 2004], WINDII on UARS, [e.g., *Ward et al.*, 1996] and more recently the line of sight (LOS) winds from the EOS MLS on Aura [e.g., *Limpasuvan et al.*, 2005; *Wu et al.*, 2008; *Limpasuvan and Wu*, 2009].

[7] These studies have complemented ground-based observations of the seasonal behavior, latitude and height structure of the wave. They also revealed that the zonal wave number structure of the 2 day wave is a complex of several different wave numbers. The largest amplitude wave numbers are the westward propagating zonal wave numbers 2, 3 and 4 (hereafter W2, W3 and W4, respectively). So the 2 day wave complex is primarily made up of these wave numbers with the W3 and W4 waves being the most significant. The W3 reaches larger amplitudes in the Southern Hemisphere than in the Northern Hemisphere. In contrast, the W4 component reaches larger amplitudes in the Northern Hemisphere [e.g., *Limpasuvan et al.*, 2000; *Riggin et al.*, 2004; *Garcia et al.*, 2005]. These observations and others have revealed a general structure for the 2 day wave in temperature and wind amplitudes. The meridional wind amplitudes were found to dominate over the zonal wind amplitudes toward the equator. At midlatitudes meridional and zonal amplitudes are similar and in general, the Southern Hemisphere wind amplitudes are double that of the Northern Hemisphere wind amplitudes in summertime. Temperature and geopotential height amplitudes were also found to maximize at middle latitudes in summertime.

[8] A number of different mechanisms have been proposed for the excitation for the 2 day wave. *Salby and Roper* [1980] proposed it to be the manifestation of the gravest zonal wave number 3 Rossby-gravity normal mode. Alternatively, *Plumb* [1983] and *Pfister* [1985] proposed that the wave is generated by a baroclinic instability of the summertime middle atmosphere westward zonal jet. Later work has suggested that both mechanisms may play a part; in particular, *Salby and Callaghan* [2001b] suggested the wave exhibits characteristics of both the normal and unstable modes and suggested that the global Rossby-gravity wave mode could grow by drawing energy from the zonal winds. In this explanation, wave energy is transferred from the mean flow to the wave in a relatively restricted region near the wave's critical line, and then disperses globally into the planetary-scale structure of the 2 day wave. In the case of the W4, *Plumb* [1983] and *Pfister* [1985] suggested that the W4 is solely due to an instability mode. *Rojas and Norton* [2007], investigated how a global Rossby-gravity normal mode might amplify from a local instability. They examined the growth rates of the wave in both linear and nonlinear models and proposed that the summertime amplification of the 2 day wave results from the interaction of the global-scale Rossby-gravity mode and a local mode excited by instabilities associated with the reversed potential vorticity gradients caused by the summer westward zonal jet. Note that the experimental study of *Offermann et al.* [2011]

suggested that the wave amplitude is related to the meridional gradient of quasi-geostrophic potential vorticity and baroclinic instabilities.

[9] In this study we use EOS Aura MLS (Microwave Limb Sounder) measurements of atmospheric temperature in the stratosphere and mesosphere to investigate the summertime 2 day wave. Data between latitudes of 70°N and 70°S are used covering the time period of September 2004 to December 2009. These data are used to develop climatologies of the 2 day wave.

[10] The key focus of this work is (1) to determine the seasonal evolution of the different wave numbers W2, W3 and W4 over the course of the summer, (2) to determine a climatology of the different wave numbers over an extended interval of time (5 years), and (3) to characterize the interannual variability of each wave number W2, W3 and W4, in terms of the interannual variability of the seasonal evolution for each component and the interannual variability in the amplitude of the 2 day wave in the summer hemisphere iv) to determine the magnitude of any aliasing effect that might produce spurious waves in the analysis used to extract 2 day waves from the satellite data set.

2. Data Analysis

[11] The source of data used in this study is the Microwave Limb Sounder (MLS) instrument aboard the NASA Earth Observing System (EOS) Aura satellite, which is part of the A train constellation of satellites. MLS uses microwave emissions in the range 118 GHz to 2.5 THz to measure temperature and composition in the lower and middle atmosphere. The Aura satellite is in a Sun-synchronous orbit, and so it passes through two local times at any given latitude. The range of latitude accessible to the satellite is approximately 82°N to 82°S. Measurements are performed along the suborbital track. The spatial resolution is approximately 500 km horizontally and 3 km vertically, decreasing to about 10 km near the mesopause [*Livesey et al.*, 2007]. A more detailed description of EOS Aura MLS is given by, e.g., *Waters et al.* [2006]. Here we use the temperature from the level 2 version 2.2 data product over the height range ~10–97 km. The data were screened as recommended by the data quality document of *Livesey et al.* [2006]. This means that the data products were only used if the precision was positive, the quality was greater than 0.6 and convergence is less than 1.2, and the status was even. The temperature precision is 1 K or better from 316 to 3.16 hPa, degrading to ~3 K at 0.001 hPa. The vertical resolution is 3 km at 31.6 hPa and 6 km at 316 hPa and only ~13 km at 0.001 hPa [*Schwartz et al.*, 2008]. The data are considered from the interval September 2004 to December 2009.

[12] In order to extract the 2 day wave signal from the temperature data, the least squares fitting method of *Wu et al.* [1995] was used. This method has earlier been used to identify the 2 day wave in UARS measurements. The method has subsequently been successfully applied to EOS Aura MLS temperature and geopotential height measurements [e.g., *Limpasuvan et al.*, 2005; *Baumgaertner et al.*, 2008; *Sandford et al.*, 2008; *Limpasuvan and Wu*, 2009; *Offermann et al.*, 2011]. The method has the advantage that it can be used with nonuniform or irregular sampling pattern, but is more computationally intensive than alternative approaches such as fast Fourier transform (FFT) or asynoptic transforms. The advantages and disadvantages of the method have been discussed in depth by *Wu et al.* [1995].

[13] In our application of the method here, sinusoidal functions with periods incremented in 1 h steps between 40 and 60 h period were least squares fitted to the satellite data in a 12 day window on each pressure level in the data set. On each pressure level the data were sorted into bands of 10 degrees latitude from 80°N to 80°S. The data points used in the fitting thus consisted of those parts of the track profiles that fall within a particular 10 degree latitude band and within a particular 12 day time window on a particular pressure level. This window was then incremented through the time series in steps of 3 days. The sinusoidal wave functions fitted had zonal wave numbers 4 to −4, where positive wave numbers correspond to westward propagating waves and negative to eastward propagating waves. For each wave number the wave period at which maximum amplitude occurred was recorded and taken to be the period of the 2 day wave in that particular 12 day window. The analysis was carried out for latitudes between 82°N to 82°S and for heights between ~10 and 97 km. The pressure levels are converted to height in the figure labels for easy comparison with radar observations.

[14] This analysis yields a final data product which is time series of temperature amplitudes, phases and periods for wave numbers 4 to −4, within a particular latitude band. Before these results can be interpreted, however, we need to consider the effects of standard errors in the best fitting process and the possibility of aliasing between different wave numbers.

[15] First, we will consider the standard error in the amplitude of the wave measured by the least squares fit. In addition to the amplitude of a particular wave fitted to the data, the least squares analysis also yields the standard error of that fitted amplitude. Considering the whole data set, these standard errors in amplitude are found to be generally between about ±0.3 and ±1.2 K and mostly toward the lower end of this range. As an example, Figure 1 presents contours of the standard error for the case of the W3 wave as a function of time and latitude at a height of 91 km. These results are presented as being typical of the standard errors yielded by this analysis. The standard errors in the case of Figure 1 are not constant, but vary from less than ±0.2 K up to about ±0.6 K. We examined the standard errors for other heights and latitudes and for other wave numbers and found the maximum standard errors in amplitude never exceeded ±1.4 K and were almost always ±0.5 K or less (results not shown for reasons of space.) We therefore will use ±1 K as a representative minimum amplitude a wave must have to be regarded as significant, taking 2 times the standard error as a threshold for significance. This is a slightly pessimistic threshold, but does allow us to use a simple standard cut off in the presentation of our results.

[16] Second, we will consider the effects of aliasing. The nature of the sampling offered by satellite measurements can lead to significant aliasing between different zonal wave number and period combinations. This could give rise to spurious results in which significant amplitudes are calculated for a particular wave number and frequency where no

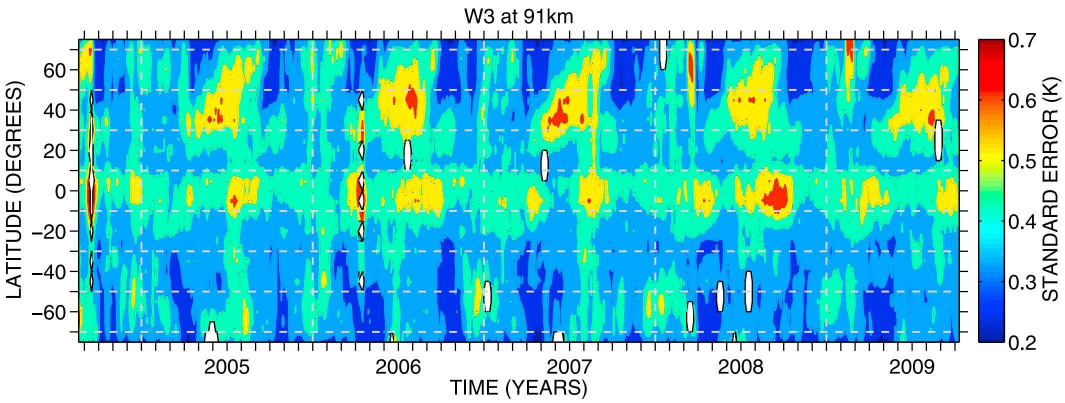

Figure 1. The temperature amplitude uncertainties of the W3 2 day planetary wave. The results are shown for a height of 91 km in the mesosphere as a function of latitude and time.

wave is actually present in the atmosphere with that wave number and frequency, and the amplitude has actually been aliased from another wave altogether.

[17] This problem has been considered in depth by *Salby* [1982a, 1982b], *Wu et al.* [1995] and *Meek and Manson* [2009], who also considered aliasing in the specific case of 2 day waves. In the analysis presented here, we are aware that aliasing between different wave numbers could be a significant issue. In particular, we need to be able to distinguish between real waves in the atmosphere and spurious results caused by the aliasing of amplitude from other wave numbers.

[18] We have examined the possible impact of aliasing on our results by modeling as follows. For each wave number −16 to 16, a synthetic data set was created in which a wave of arbitrary amplitude was present at that particular wave number with a wave period of 48 h and of constant amplitude from pole to pole. This data set was then sampled using the same spatial and temporal sampling as that of the EOS Aura MLS data and the results examined to see how much amplitude was present in other wave numbers and frequencies as a result of aliasing from this particular wave.

[19] Figure 2 presents the results of this analysis for wave numbers −7 to 7 (the higher wave numbers not plotted because they are unlikely to correspond to real features in the atmosphere). Figure 2a presents the example case of a W3 wave of frequency 0.5 cycles per day (cpd) at a latitude of 70°S and a height of 59 km. In addition to a spectral peak corresponding to the synthetic wave, a number of other peaks are evident. In particular at wave number W3 there are a series of small "sidelobe" peaks at frequencies slightly higher and lower than 0.5 cpd. There are also three smaller peaks at frequency, wave number coordinates of 0.5, −2; 1.5, −1 and 1.5, 4 (where wave number −1 is an E1 wave, etc.). Note that such aliasing can also occur from a genuine wave at these latter periods and wave numbers resulting in a spurious aliased signal at the 0.5, 3 frequency/wave number coordinate. However, some of the signals aliased from W3 are unlikely to be mistaken for a genuine planetary wave because they occur at frequencies higher than expected for a planetary wave (e.g., the two signals at 1.5 cpd). This result shows that a significant fraction of the amplitude of a W3 2 day wave can be aliased into an E2 2 day wave (and visa versa). Finally, note that there are also signals aliased to wave number frequency coordinates outside of the regions plotted in Figure 2a. For example the 0.5 cpd W3 wave also produces an aliased signal at a wave number and frequency of 1, −11. However, these peaks are at such extreme wave numbers that we will not consider them further.

[20] A similar analysis is presented for aliasing from a 0.5 cpd W2 and W4 waves in Figures 2b and 2c, respectively. Figures 2b and 2c also reveal a pattern of aliased peaks. Again there are three peaks in each case one at 0.5 cpd and two at 1.5 cpd. Figure 2b shows an aliased signature at frequency, wave number coordinates of 0.5, −1 wave, and Figure 2c shows an aliased signature at frequency, wave number coordinates of 0.5, −3. There are again two signals for each wave number at a frequency of 1.5 cpd.

[21] We noticed that there is considerable variation in the population of aliased waves as a function of latitude. To investigate this further, we calculated the fraction of a synthetic waves amplitude that would be aliased into other wave numbers as a function of latitude. The results of this investigation are summarized in Figure 3.

[22] First, we will consider the impact on our results of an E2 wave present in the atmosphere. Such waves with periods near 2 days are known to exist in the atmosphere [e.g., *Nozawa et al.*, 2003a; *Palo et al.*, 2007; *Sandford et al.*, 2008]. Figure 3a presents the case where a synthetic E2 wave of constant arbitrary amplitude is modeled as present in the atmosphere. Figure 3a indicates the fraction (as a percentage) of the amplitude of this wave which will be aliased into W2, W3, and W4. From Figure 3a it can be seen that there is no significant aliased signal for the W2 and W4 components. However, a W3 aliased signal does result. This aliased signal varies strongly with latitude due to the nature of the sampling. The aliased W3 amplitude exceeds 40% of the E2 amplitude poleward of about 65° and decreases to very small values near the equator. This means that at high latitudes an E2 wave may produce significant amplitude aliased into the W3 wave. It is known that 2 day E2 waves exist in the high-latitude wintertime stratosphere and mesosphere [e.g., *Nozawa et al.*, 2003b; *Sandford et al.*, 2008].

[23] Consequently, any 2 day W3 signal observed at high latitude in wintertime must be treated with caution because

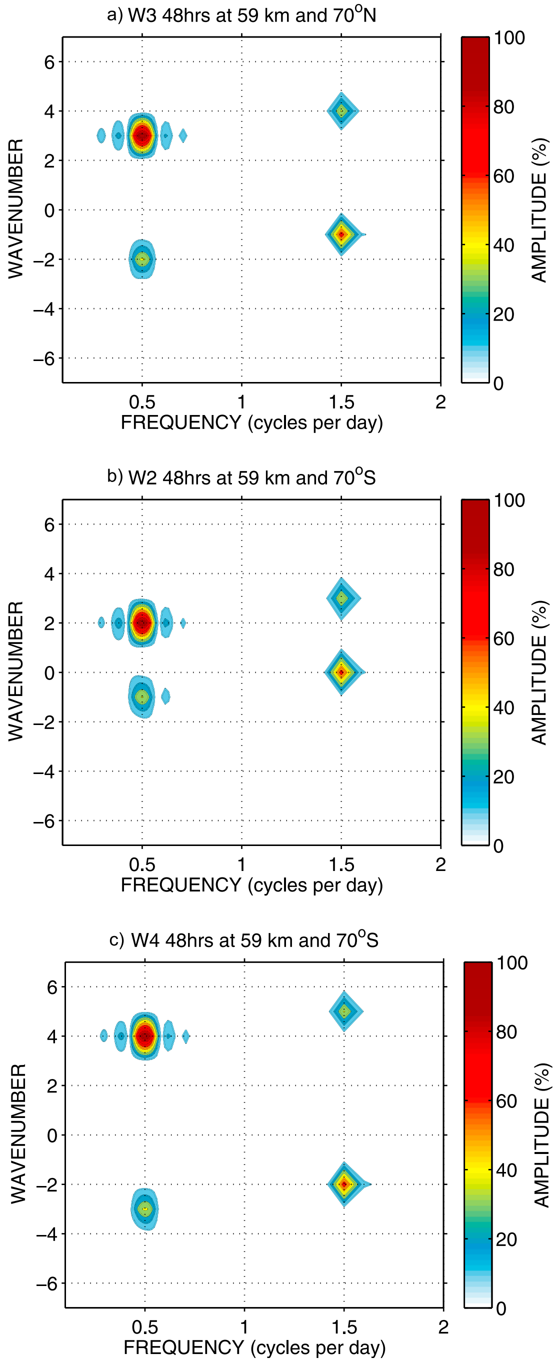

Figure 2. Aliased signals from a primary 2 day planetary wave at 0.5 cpd. This is for (a) a W3 primary wave, (b) a W2 primary wave, and (c) a W4 primary wave. Negative wave numbers refer to eastward traveling waves, and positive numbers refer to westward traveling waves.

it may be aliased from the E2 rather than being a genuine wave in the atmosphere. However, in summer it is not believed that there exists a large amplitude E2 2 day wave at high latitude so any W3 signal observed in summer will thus be genuine. We note that our conclusion that amplitudes of up to about 40% may be aliased from a 2 day E2 to a W3 is in good agreement with the value derived by *Wu et al.* [1995] in their consideration of aliasing.

[24] Second, a similar technique was applied to the E1 and E3 waves and the results are shown in Figures 3b and 3c, respectively. In Figure 3b a synthetic E1 wave of constant arbitrary amplitude is modeled as present at all latitudes. Figure 3b shows that the E1 wave produces an aliased signal

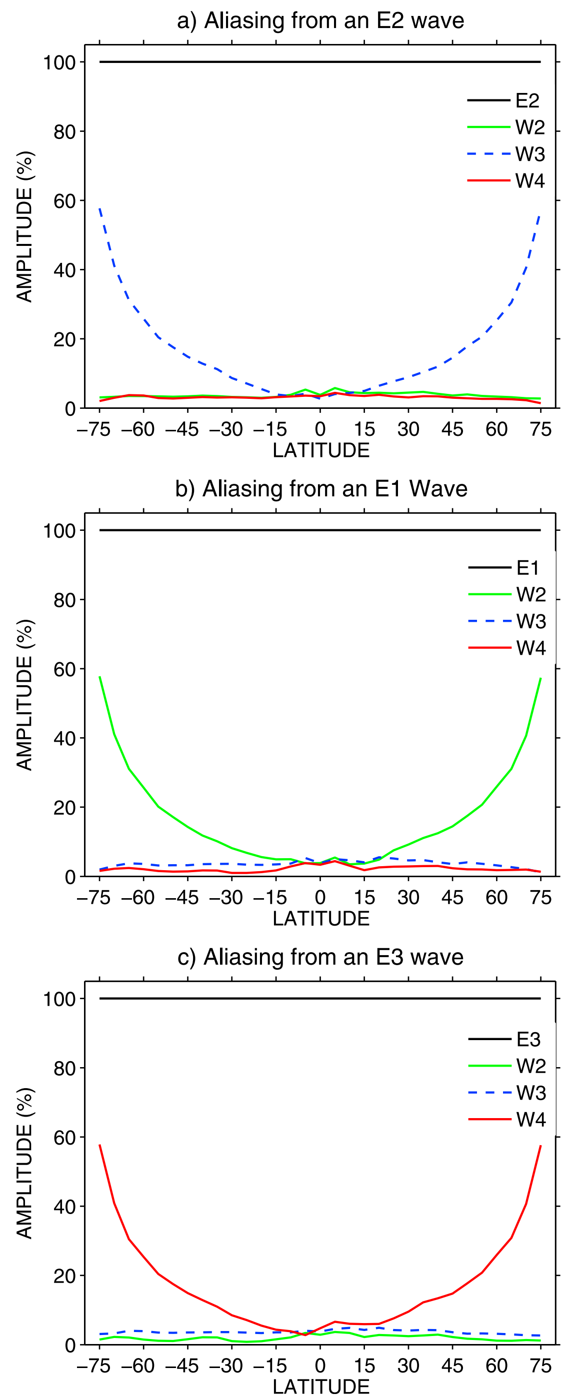

Figure 3. The fraction of wave amplitude aliased from a primary 2 day planetary wave into zonal wave numbers W2, W3, and W4 as a function of latitude for (a) an E2 primary wave, (b) an E1 primary wave, and (c) an E3 primary wave. Spacecraft sampling from July 2008 is used in the analysis.

in the W2 wave but no significant aliased signals for the W3 and W4 waves. The aliased W2 wave has a similar profile of amplitude with latitude to the results presented in Figure 3a in that it exceeds 40% of the amplitude of the E1 wave poleward of about 65° and decreases to very small relative amplitudes near the equator. Therefore, at high latitudes an E1 wave may produce a W2 wave with a significant aliased amplitude. Similarly in Figure 3c, a synthetic E3 wave is modeled as present at a constant arbitrary amplitude at all latitudes. In this case it can be seen that a significant W4 aliased amplitude can occur at high latitudes.

[25] From the above analysis we conclude that for 2 day waves, high-latitude spurious signals may arise as a result of aliasing. In particular there may be aliasing between zonal wave numbers E2/W3, E1/W2 and E3/W4. Note that aliasing between other pairs is possible if wave periods other than 2 days are considered. It is known that E1 and E2 waves exist in the atmosphere at high latitudes in winter and so the possibility of aliasing must be considered in results showing W2 and W3 waves at these latitudes and in this season. However, at middle and low latitudes the magnitude of the aliased signals is very much smaller and so aliasing is probably not a significant problem. Finally, note that this analysis cannot detect waves of tidal period. So, for example, the W6 diurnal tide proposed by *Walterscheid and Vincent* [1996] to be generated by interaction of the 2 day wave and diurnal tide cannot be detected.

3. Results

[26] The studies described in section 1 suggest significant wave amplitudes occur for components W2, W3, W4 and E2. The temperature amplitudes of the W2, W3, W4 and E2 components as a function of time, height and latitude were determined as described above and used to investigate the variability of the 2 day wave.

[27] We will now present the results for two particular heights. These are 91 km, taken as a representative height for the mesosphere and lower thermosphere (MLT) region (and because the radar results described in section 1 indicate that the summertime 2 day wave reaches maximum amplitudes at about this height) and 56 km, taken as a representative height for the stratopause.

[28] First, we present in Figure 4 the temperature amplitude time series of the 2 day wave for W2, W3, W4 and E2 components at a height of 91 km and for latitudes between 75°N and 75°S (latitudes poleward of this are not plotted because of the aliasing issues discussed in section 2). The data span the interval September 2004 to December 2009. Contours are not plotted for amplitudes smaller than the 1 K threshold identified in section 2.

[29] We will now consider the variability of these waves in terms of their seasonal and latitudinal behavior. We will also consider differences between the Northern and Southern Hemispheres. Figure 4 shows there are significant 2 day wave amplitudes in all four wave numbers and these wave amplitudes vary strongly with season and latitude.

[30] The W2 amplitudes of Figure 4a are largest at middle to low latitudes and occur throughout the year as a series of isolated bursts of activity lasting a few tens of days and generally having amplitudes of less than 2.5 K. Significantly larger wave amplitudes occur in January of each year, where wave amplitudes exceed 3 K. This occurs simultaneously in both hemispheres and so the W2 activity is strongest in Southern Hemisphere summer and Northern Hemisphere winter. For example, in January 2006 wave amplitudes exceed 3 K in both hemispheres at latitudes near 20°. A similar burst of increased wave activity is evident in January 2008. In both cases the wave amplitude is largest in the Southern Hemisphere in summer. Strong interannual variability is evident. For example, in January 2006 and 2008 wave amplitudes exceed ~3 K in both hemispheres in 2006 and in the Southern Hemisphere only in 2008. For the rest of the years wave amplitudes are smaller, reaching only ~2 K.

[31] The W3 amplitude of Figure 4b include episodes where the wave amplitudes are significantly larger than those of the W2 component. A very clear seasonal behavior is again evident and there are some significant differences in the wave between the Northern and Southern Hemispheres.

[32] Considering first the Southern Hemisphere, it can be seen that the W3 reaches amplitudes in excess of 3 K in January of all years. This summertime wave activity extends from very close to the equator to the highest latitudes observed. The largest amplitudes generally occur at latitudes near 40°S. There is little evidence of significant W3 amplitude at other times of year in this hemisphere. Considerable interannual variability is evident. For example, in January 2006 wave amplitudes exceed 3.5 K for latitudes ranging from 25°S to 50°S. The peak amplitude is 12 K. In contrast, in January 2008 amplitudes never rise above 3.5 K and wave activity is confined to a relatively narrow range of latitudes from ~20°S to 60°S. Note that the large-amplitude W3 wave event in January 2006 was extensively studied by *Limpasuvan and Wu* [2009].

[33] In contrast to the Southern Hemisphere, significant W3 wave amplitudes occur in both summer and winter in the Northern Hemisphere. Wave amplitudes are quite variable and sometimes the winter maxima equal the summer ones. Amplitudes are rather less than in the Southern Hemisphere and peak amplitudes are usually only about 3 K. Peak amplitudes occur at latitudes of ~30°N–40°N. It is noticeable that when large W3 amplitudes occur in the Northern Hemisphere winter they occur simultaneously with the strong W3 activity in the Southern Hemisphere summer, suggesting significant interhemispheric propagation of the W3 wave under those conditions. Interannual variability is again evident. For example wave amplitudes in the summer of 2006 exceed 3 K whereas in summer 2005 they reach only ~2.2 K.

[34] The W4 component is presented in Figure 4c. Again, a strong seasonal cycle and clear interhemispheric differences are evident. In contrast to the W3, the largest amplitudes are observed in the Northern Hemisphere. Again, wave activity occurs in relatively short-lived bursts. These occur most strongly in Northern Hemisphere summer (July–August) where wave amplitudes reach ~3.5 K. Largest amplitudes occur between 30°N and 40°N and wave amplitudes are insignificant poleward of 60°N. The amplitude again varies from year to year. No significant W4 wave activity is evident in Northern Hemisphere winter.

[35] In the Southern Hemisphere, the W4 also occurs only in summer and is strongest in February of all years observed. W4 wave amplitudes are smaller than in the Northern Hemisphere with peak amplitudes ranging from 1.5 to 2.5 K, except for in 2009 where they reach 3.5 K. Again, strong

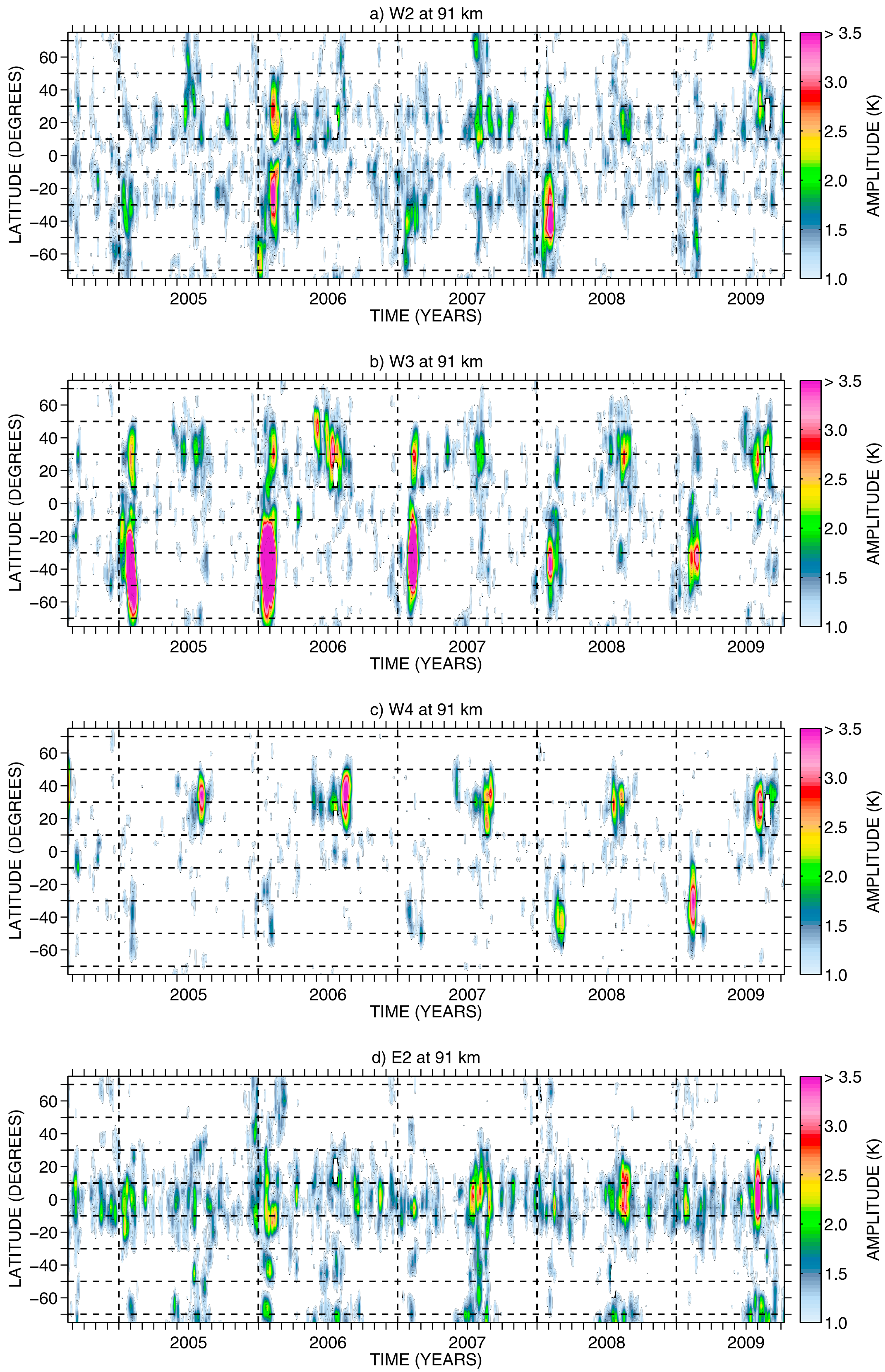

Figure 4. The temperature amplitude of 2 day planetary waves at a height of 91 km in the mesosphere as a function of latitude and time. Amplitudes below 1 K are not plotted. The results are shown for wave numbers (a) W2, (b) W3, (c) W4, and (d) E2.

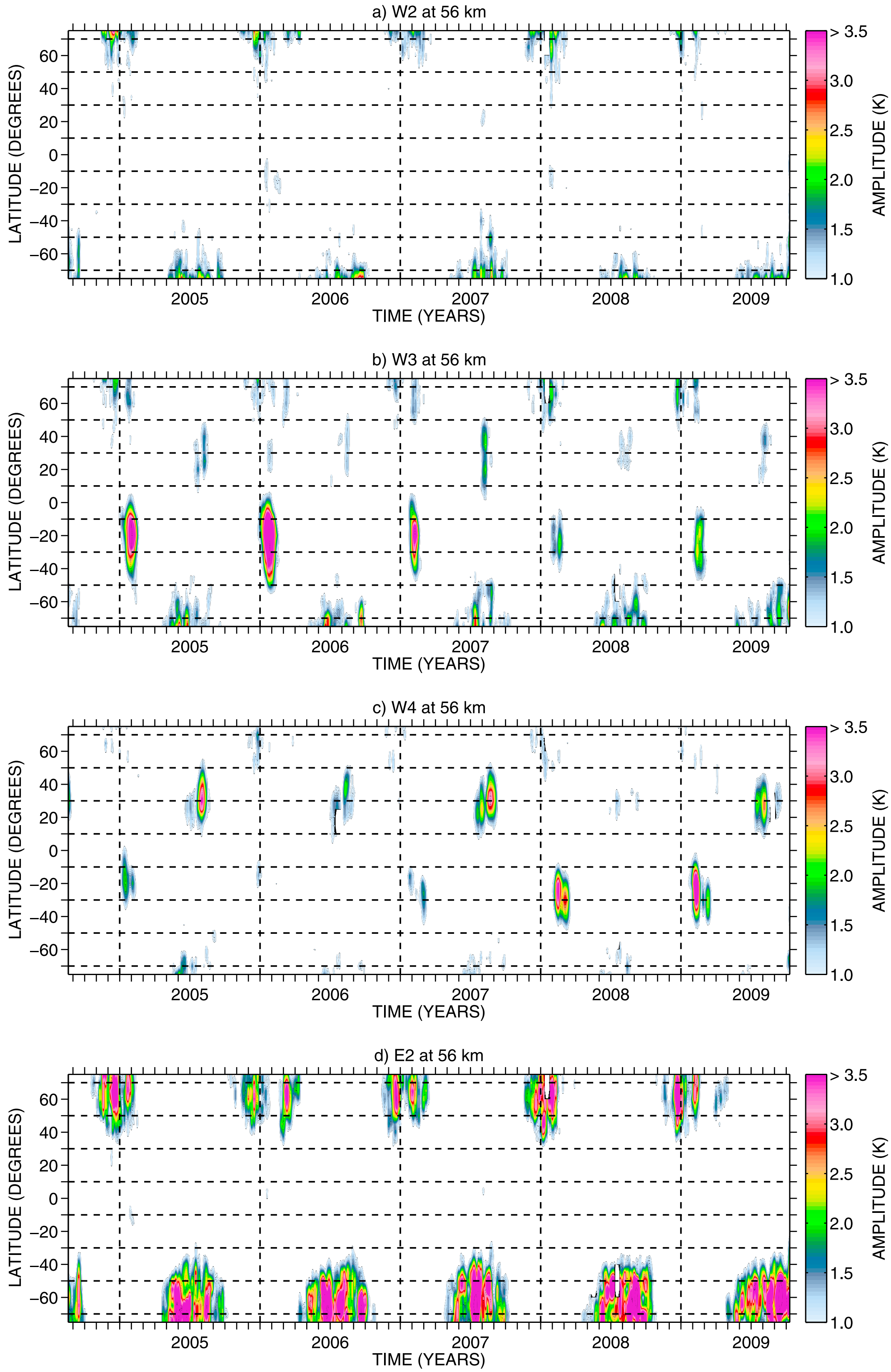

Figure 5. The temperature amplitude of 2 day planetary waves at a height of 56 km near the stratopause as a function of latitude and time. Amplitudes below 1 K are not plotted. The results are shown for wave numbers (a) W2, (b) W3, (c) W4, and (d) E2.

interannual variability can be seen. For example, in February 2009 wave amplitudes reach 3.5 K, whereas in 2008 wave amplitudes are ~2.2 K and for the rest of the years the amplitude is <1.5 K.

[36] The E2 component is presented in Figure 4d. It has largest amplitudes at latitudes between 0° and ±20°. The largest amplitude bursts occur around the summer and winter solstice. At high latitudes, E2 amplitudes generally maximize in winter. Again, a large degree of interannual variability is present. The winter polar E2 wave is also present in the Southern Hemisphere, peaking at amplitudes of over 2 K for each winter in the months of July–August.

[37] We will now consider the results of a similar analysis applied at 56 km. Figure 5 presents temperature amplitudes for W2, W3, W4 and E2 in a similar fashion to the results in Figure 4, except in this case for a height of 56 km.

[38] The W2 component, shown in Figure 5a, maximizes at high latitudes in winter in both hemispheres. The wintertime maxima typically have durations of 3–4 months. Peak wave amplitudes are ~3 K or less. Within each winter season the amplitudes are quite variable with fluctuations in amplitude occurring on timescales as short as a few tens of days. This seasonal and latitudinal variability is quite different from that observed at ~91 km (Figure 4a), where wave amplitudes peak at much lower latitudes. However, we believe this signal is almost certainly the result of aliasing from an E1 wave as described in section 2.

[39] The W3 component, shown in Figure 5b, reveals a generally similar seasonal cycle to that evident at 91 km. Again, wave amplitudes are largest in the Southern Hemisphere, where they exceed 3.5 K in three of the five summers observed. In contrast, Northern Hemisphere W3 amplitudes generally reach only ~2 K. The W3 wave occurs in short-lived bursts in summer and maximizes at middle latitudes in both hemispheres. The interannual variability appears to follow a similar pattern to that evident at 91 km. However, there is a noticeable difference in that significant wave amplitudes appear to occur at high latitudes in winter in both hemispheres. However, we believe that this high-latitude signal is a consequence of aliasing from the high-latitude E2 winter wave (see the discussion on aliasing in section 2 and the results of Figure 5d).

[40] The W4 component is shown in Figure 5c. As with the W3 component, the seasonal behavior is quite similar to that observed at 91 km. Again, as at 91 km, wave amplitudes are largest in the Northern Hemisphere. They are largest in short-lived bursts in summer and the amplitudes maximize at midlatitudes. The pattern of interannual variability, however, is slightly different from that observed at 91 km. For instance, the W4 amplitude in Northern Hemisphere summer of 2006 at 56 km is smaller than the amplitudes observed in either 2005 or 2007, whereas at 91 km the Northern Hemisphere summer amplitudes in 2006 are the largest observed in any year of the data set.

[41] The E2 component is shown in Figure 5d. Unlike the situation at 91 km (Figure 4d) here the E2 maximizes at high latitudes in winter. It is almost entirely absent at low latitudes and in summer. Significant wave amplitudes occur from December to February in the Northern Hemisphere and May to September in the Southern Hemisphere. The onset and cessation of wave activity is quite abrupt in both hemispheres.

[42] This wintertime, high-latitude E2 wave appears to be the same phenomenon identified by other authors [e.g., *Nozawa et al.*, 2003a; *Sandford et al.*, 2008]. Note that the high-latitude wintertime W3 of Figure 5b almost certainly results from aliasing from this E2 wave.

[43] To investigate the vertical structure of the waves, wave amplitudes as a function of time and height were considered. As examples of this analysis, Figure 6 presents the temperature amplitudes of W2, W3, W4 and E2 as functions of height and time. In the case of W2 (Figure 6a) the data are presented for a latitude of 40°S since this is where the largest amplitudes occur. The results for W3, W4 and E2 are presented for latitudes of 40°S, 40°N and 70°S, respectively, because these wave numbers maximize at those particular latitudes.

[44] Considering the W2 results of Figure 6a, it can be seen that wave amplitudes are greatest between 80 and 100 km. Wave amplitudes are generally not significant below 70 km. The interannual variability evident in Figure 4a, is also evident in this presentation. However, the height at which maximum amplitude occurs is quite consistent from year to year.

[45] The W3 results for a latitude of 40°S are shown in Figure 6b. Figure 6b shows that wave amplitudes maximize at about 80 km in each year. The wave amplitudes go down to very small values, generally less than ~1.5 K, below 55 km. At the greatest heights observed the wave amplitudes appear to be declining. As in Figure 4b, large amplitudes occur only for a short time after the summer solstice and wave amplitudes are much smaller outside these times. Interannual variability is very strong; for example, in January 2006 wave amplitudes are 12 K, whereas in February 2008 and February 2009 wave amplitudes reach only about 5 K. Again, despite interannual variability in amplitude, the height at which amplitude maxima occur is remarkably consistent.

[46] The results for W4 are shown for a latitude of 40°N in Figure 6c. As with the W3, the largest wave amplitudes occur in short bursts in late summer and are largely absent at other times of the year. Again, wave amplitudes display strong interannual variability. For example, wave amplitudes exceed 6 K in August 2006 but only reach ~4 K in July 2008. Despite this variability, the height of maximum amplitude is relatively consistent at about 75 km. Wave activity is evident at heights from about 55 km to the greatest height observed. As with the W3, the amplitudes reduce somewhat toward the greatest heights observed.

[47] The E2 wave maximizes at high latitudes as shown in Figure 5d. We will therefore consider the amplitude as a function of height for the E2 at 70° latitude rather than the 40° considered above. Figure 6d presents the E2 amplitudes at 70°S. It can be seen that the wave occurs in short bursts throughout the winter and spring months (June–September). Wave amplitudes maximize between 40 and 70 km, where they can reach ~8 K. Above these heights the wave amplitudes reduce, but the wave is still clearly evident to heights of about 100 km. At these upper heights the amplitudes are generally about 2 K or less. It is this wintertime MLT region wave activity at high latitude that has been reported in the radar and/or satellite studies of, e.g., *Nozawa et al.* [2003a] and *Sandford et al.* [2008].

[48] In order to get a better understanding of the latitude-height structure of the various wave numbers, the previous sets of data were combined into height-latitude contour plots

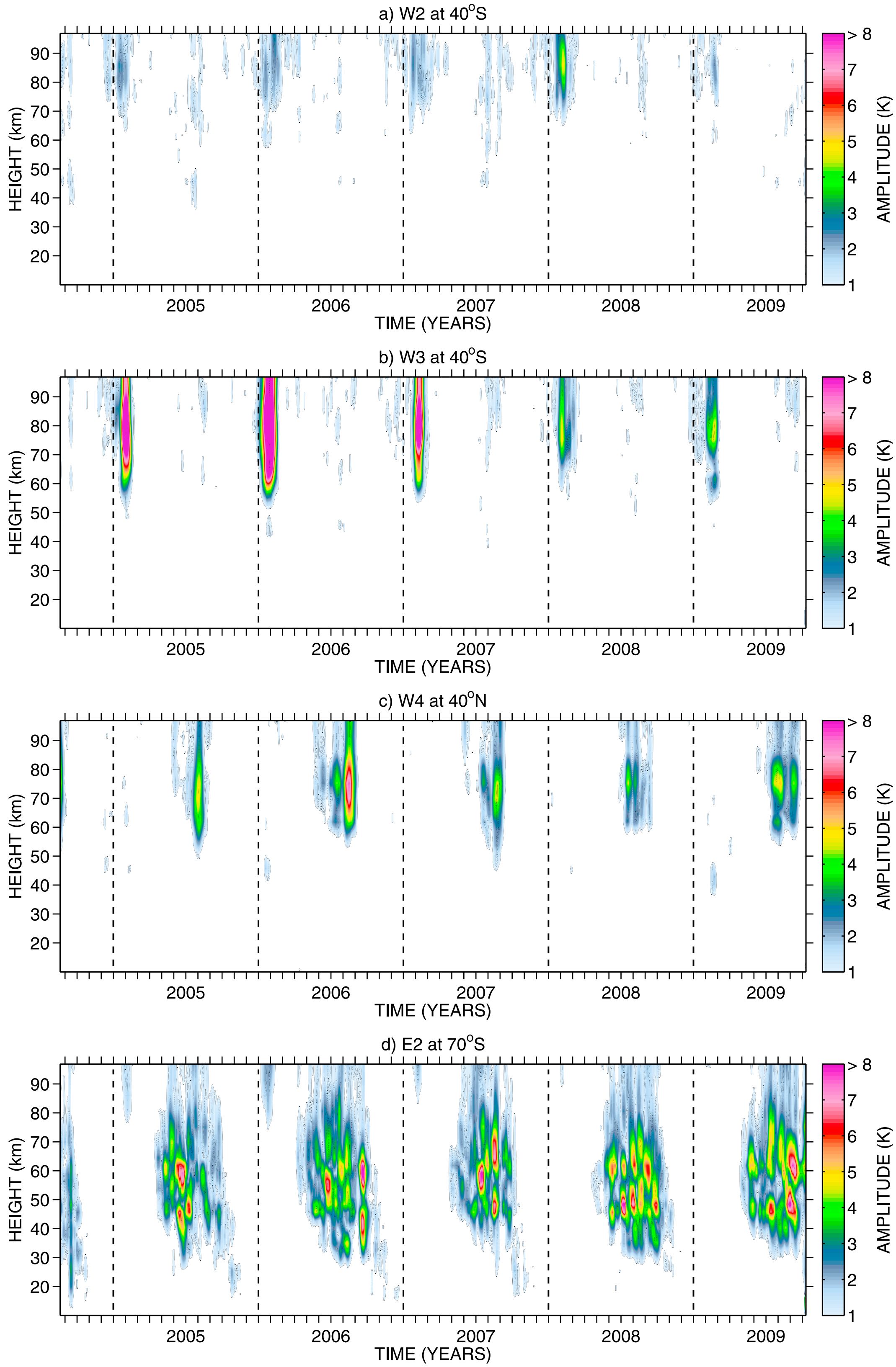

Figure 6. The temperature amplitude of 2 day planetary waves as a function of height and time. Amplitudes below 1 K are not plotted. The results are shown for wave numbers (a) W2 at 40°S, (b) W3 at 40°S, (c) W4 at 40°N, and (d) E2 at 70°S.

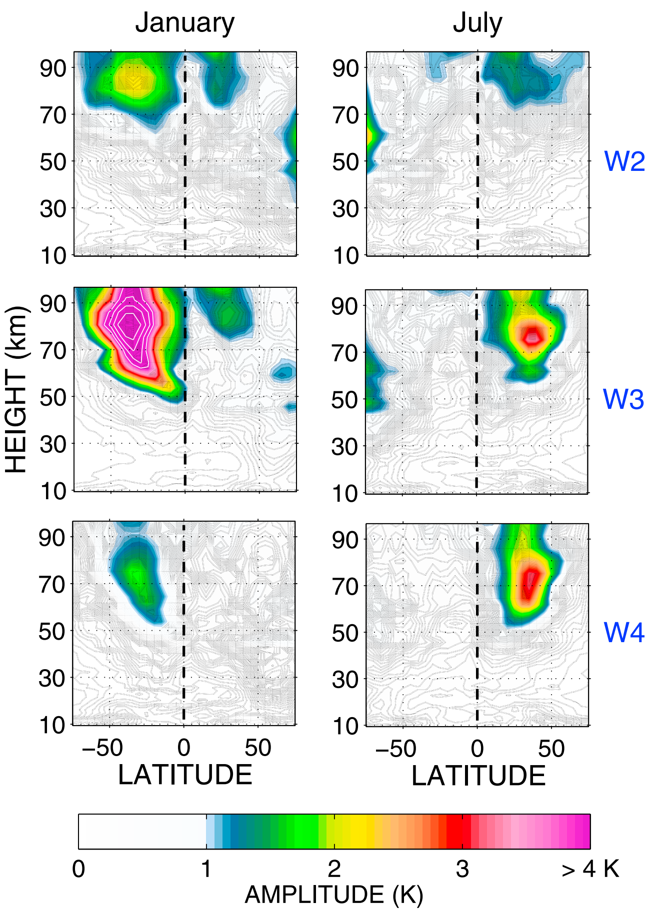

Figure 7. Composite year plots of 2 day wave temperature amplitudes as function of height and latitude in January and July for wave numbers W2, W3, and W4. White contours are in steps of 0.5 K.

for each month and then all the individual months were averaged to produce a set of composite months. Figure 7 presents the results of this composite month, or superposed epoch, analysis as plots of the temperature amplitude of the 2 day wave component wave numbers as a function of height and latitude for the W2, W3, W4 wave numbers, between 2004 and 2009 for January and July (plots for individual months and wave numbers in the various years are not shown for reasons of space).

[49] It is evident from Figure 7 that the W2 temperature amplitude maximizes in the upper heights observed, typically between 85 and 90 km. For example, the largest amplitudes observed are ~2.2 K at heights near 80 km in the Southern Hemisphere in January at latitudes near 35°S. Northern Hemisphere amplitudes are somewhat smaller reaching to only about 1.5 K. There appears to be some penetration of the wave into the winter hemisphere from the Southern Hemisphere summer wave. There also appears to be significant W2 wave amplitudes around the stratopause at high latitudes in winter. For example, in the Northern Hemisphere in January and in the Southern Hemisphere in July. However, as discussed in section 2, this is most probably the aliased signature of a high-latitude E1 wave.

[50] The mean W3 temperature amplitude maximizes at midlatitudes at heights of ~80 km in summer in both hemispheres, i.e., similar to the heights at which the W2 maxima occur. W3 amplitudes are large, reaching up to 6 K in January in the Southern Hemisphere and 3 K in July in the Northern Hemisphere. This presentation highlights the fact noted earlier that the W3 wave amplitudes are significantly larger in the Southern Hemisphere than in the Northern Hemisphere. As with the W2 there also appears to be some penetration of the wave into the winter hemisphere from the Southern Hemisphere summer wave. The high-latitude W3 activity occurring at the winter stratopause is most probably a result of aliasing from the E2 wave as discussed in section 2.

[51] The W4 temperature amplitude maximizes at a height of ~70–80 km at midlatitudes in summer in both hemispheres. The W4 wave thus maximizes at a slightly lower height than that at which the W2 and W3 maximize. In contrast to the W2 and W3 components, the largest W4 amplitudes occur in the *Northern* Hemisphere where mean wave amplitudes exceed 3 K in July, whereas wave amplitudes are somewhat smaller in the Southern Hemisphere at 1.5 K.

[52] Figure 7 suggests that there is some wave activity at high latitudes in *winter* for the W2 and W3 components; for example, in July in the Southern Hemisphere. However, as mentioned earlier we believe this high-latitude wintertime wave activity can in fact be explained as a result of the aliasing processes discussed in section 2. There are two reasons for this conclusion.

[53] First, strong evidence that these high-latitude wintertime W3 signals are aliased is provided by the fact that their latitude and height structure are very similar to those of the larger-amplitude E2 wave observed simultaneously (not shown in Figure 7 for reasons of space). In particular, the amplitude maxima occur just above and below 50 km and the waves are observed only at high wintertime latitudes. Critically, we also note that the results of Figure 3a suggest that such aliasing could occur strongly only at high latitudes and can occur between E2 and W3 waves. We therefore conclude that these high-latitude wintertime W3 waves are primarily an aliased signature of the much stronger E2 wave.

[54] Secondly, similar arguments to the above suggest that the high-latitude wintertime W2 signals are also aliased, in this case from an eastward propagating zonal wave number one oscillation (E1, not shown in Figure 7 for reasons of space). Again, the results of Figure 3b suggest that such aliasing could occur strongly at high latitudes between the E1 and W2 waves.

[55] If we consider the full set of results presented above, we can identify several important features of the 2 day wave. These include the following:

[56] 1. The wave is a complex composed of W2, W3 and W4 components.

[57] 2. Aliasing from the winter-polar E2 wave is evident in the W3 component in this data set.

[58] 3. The seasonal and latitude-height structure of the W2, W3 and W4 waves are similar to first order but do include some significant differences. For example, significant W2 and W3 amplitudes are evident from the equator to high latitudes in the Southern Hemisphere summer. This

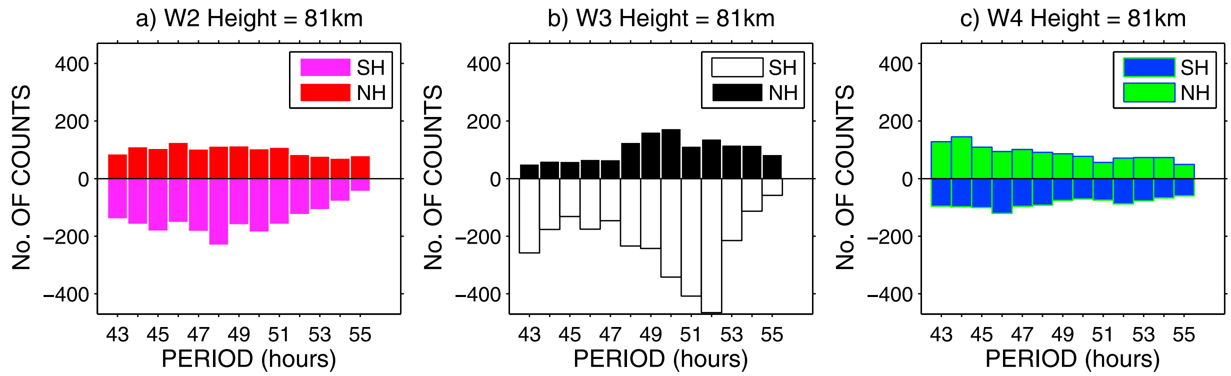

Figure 8. Histograms of wave period of zonal wave numbers (a) W2, (b) W3, and (c) W4. Data from summer only are used. In the Northern Hemisphere the data are from June, July, and August, and in the Southern Hemisphere the data are from December, January, and February.

may simply reflect the larger amplitudes reached by the W2 and W3 in Southern Hemisphere summer.

[59] 4. The W2, W3 and W4 waves all reach maximum amplitudes at heights between 75 and 90 km.

[60] 5. There is a high degree of interannual variability and the peak amplitudes can vary by a factor of more than 3 from year to year.

[61] In order to investigate the differences between the climatologies of the W2, W3 and W4 waves, their behavior was examined in more detail. Because these waves maximize in summer we will consider data from June to August in the Northern Hemisphere and December to February in the Southern Hemisphere. All the waves have largest amplitudes at heights between about 75 and 90 km so we will consider a height of 81 km. The particular question we will address is How do the relative contributions to the 2 day wave complex of the W2, W3 and W4 components change over the course of a summer? To do this, we calculated the wave amplitudes and periods using the least squares method described in section 2.

[62] First, we will consider the wave periods associated with wave numbers W2, W3, W4 (identified above as the largest amplitude waves in summer). Figure 8 presents the wave periods of these particular wave numbers as calculated from all available years of data and all latitudes at a height of 81 km as follows. In each hemisphere, for each 12 day window described in section 2 the wave period was calculated and recorded. The periods were then weighted against the amplitude of the wave and were then used to produce histograms of the frequency of occurrence of particular wave periods. Figure 8 presents the results of this analysis for the three wave numbers W2, W3 and W4 calculated using only the summer data from each hemisphere. If we consider Figure 8 we can see that all three components can occur with a range of periods. The W2 has periods generally between 44 and 51 h. The W3 has periods generally between 48 and 52 h. The W4 generally has shorter periods, usually less than 48 h.

[63] Second, we will consider the evolution over summer of the wave amplitudes associated with wave numbers W2, W3, W4. Figure 9 presents the wave amplitudes of each component throughout the summer season for both hemispheres. The interhemispheric asymmetry evident in the earlier results is very clear in Figure 9. For example, the amplitude of the W3 is very much greater in the Southern Hemisphere than the Northern Hemisphere in 2004/2005, 2005/2006 and 2006/2007. Peak amplitudes reach 12 K in the summer of 2005/2006 in the Southern Hemisphere, whereas Northern Hemisphere amplitudes reach only 3–4 K. However, note that in the last two summers observed (2007/2008, 2008/2009) the Southern Hemisphere W3 amplitudes are in fact rather similar to those of the Northern Hemisphere. This appears to be the main cause of interannual variability; that is, the main interannual variability comes from year-to-year fluctuations in the amplitude of the W3 component in the Southern Hemisphere.

[64] In contrast, the amplitudes of the W2 and W4 components appear rather similar in the two hemispheres. The W2 amplitudes are generally less than about 3 K throughout the summer and the W4 amplitudes can reach as high as 6 K (e.g., 2006 in the Northern Hemisphere). The largest W3 amplitudes are in most summers quite short-lived compared to the W4 component and so at the end of summer the W4 amplitudes are usually greater. This behavior is seen in most years and is most prominent in, for example, the Northern Hemisphere summers of 2004, 2006, 2007 and 2009 and the Southern Hemisphere summers of 2007/2008 and 2008/2009. In other words, in the middle of summer the 2 day wave is dominated by the W3 component, but by the end of summer it has become dominated by the W4 component.

[65] To examine this behavior in more detail, we averaged the data regardless of the year to produce superposed epoch summers for latitudes of 40°N and 40°S at a height of 81 km. Figure 10 presents these data for W2, W3 and W4 components with the data from each hemisphere presented on the same plot to enable comparison. From Figure 10 it can be seen that the mean W2 amplitudes are generally quite similar in both hemispheres although slightly larger in the Southern Hemisphere. The mean W3 component is again seen to be significantly larger in the Southern Hemisphere, 7.5 K compared to ~3 K in the Northern Hemisphere. Further, W3 amplitudes appear to maximize slightly later in the summer in the Southern Hemisphere. Mean W4 amplitudes are significantly larger in the Northern Hemisphere throughout the summer. As noted earlier, W4 amplitudes remain large until well into late summer (February/

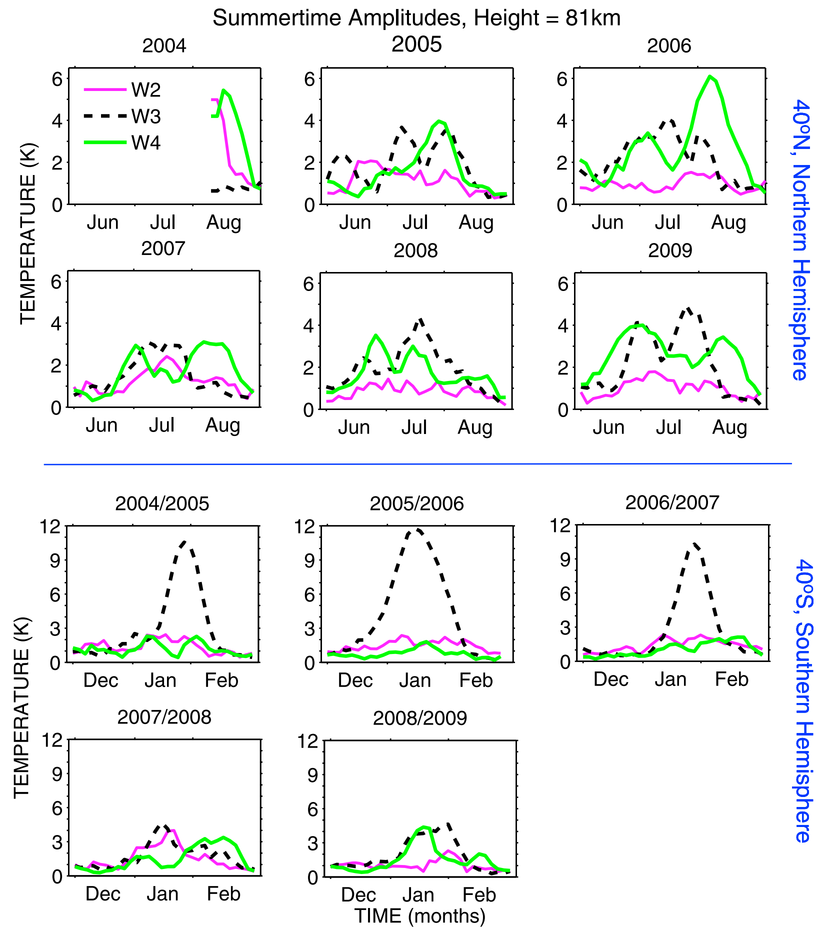

Figure 9. The amplitude of the component wave numbers W2, W3, and W4 of the 2 day wave in summer at a height of 81 km. (top) Data from June to August from 2004 to 2009 at 40° in the Northern Hemisphere. (bottom) Data from December to February 2004/2005 to 2008/2009 at 40° in the Southern Hemisphere.

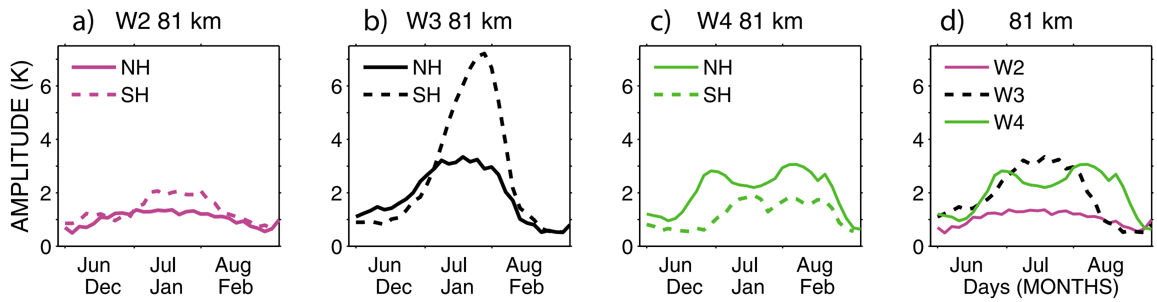

Figure 10. Composite year amplitudes of the component wave numbers of the 2 day wave in summer at a height of 81 km for both hemispheres and for wave numbers (a) W2, (b) W3, and (c) W4 and (d) superposed epoch results for all three wave numbers in the Northern Hemisphere.

August) where they then exceed the W3 amplitudes, resulting in a 2 day wave which is primarily a W4 oscillation at the end of summer. This is illustrated further in the case of the Northern Hemisphere in Figure 10d, which presents the superposed epoch results for all three wave numbers, but only for the Northern Hemisphere. It can be seen that mean W3 amplitudes have declined to small values in August but that there is still apparent amplitude in the W4 component.

4. Discussions

[66] The global pattern of 2 day wave activity in terms of height, latitude and season presented above provides a planetary-scale overview of the structure of the 2 day wave. The ground-based observations described in section 1, provide localized measurements that can be seen to fit with good agreement into this overarching context. In particular, the total level of 2 day wave amplitude (i.e., the sum of wave amplitudes from wave numbers W2, W3 and W4) maximizes after the summer solstice at midlatitudes and in the upper mesosphere and is largest in the Southern Hemisphere.

[67] A significant feature of our observations is the very different amplitudes and seasonal variation in amplitude exhibited by the W2, W3 and W4 components. A limited number of modeling studies have attempted to explain the relative contributions of different waves with periods near 2 days to the total of observed 2 day wave activity. *Salby and Callaghan* [2001b] considered the growth of waves with periods near 2 days and wave numbers of W1, W2, W3 and W4. Wave activity generated by instabilities near the wave's critical line was found to disperse globally into Rossby-gravity modes. In conditions of strong easterly winds around the solstice, the *e*-folding times for the growth in amplitude of the four wave numbers W1 to W4 were found to be approximately >40, >40, 5 and 10 days, respectively.

[68] These slow growth rates for the W1 and W2 may well explain the negligible W1 and small W2 amplitudes we observe and the larger solstitial amplitudes we observe for the W3 and W4. In the weaker easterlies of later summer (specifically, July), *Salby and Callaghan* [2001b] found the W3 and W4 to amplify in the mesosphere at about the same rate. Again, this provides a plausible explanation for the comparable amplitudes of the W3 and W4 we frequently observe in late summer. We also note that the transition from a predominantly W3 to a W4 structure was also reported in the modeling study of *Norton and Thuburn* [1996]. They speculated that the wave number 4 may originate from the spectrum of wave numbers that can be excited by different zonal jet profiles, following the theoretical work of *Plumb* [1983]. This transition to similar W3 and W4 amplitudes was also observed using satellite and ground-based radars in the boreal summer of 1994 by *Riggin et al.* [2004]. They found that in the Northern Hemisphere, during summer, the W3 component had significant amplitudes during July and August. The W4 amplitudes exceeded those of the W3 in August, after the W3 had reduced from peak amplitudes. Our results show that this behavior is representative of the 2 day wave in more than 1 year.

[69] *Salby and Callaghan* [2001b] reported that very modest changes in zonal mean wind could sharply alter growth rates but had little impact on wave period or structure. This sensitivity to subtle differences in background wind conditions may, in part, explain the dramatic interannual and interhemispheric differences in amplitude evident in the W3 and W4 components. *McCormack et al.* [2009] examined the 2 day wave in January 2006 using global synoptic fields in the Navy Operational Global Atmospheric Prediction System Advanced Level Physics, High Altitude (NOGAPS-ALPHA) forecasting assimilation system. They found evidence for a relationship between the disturbed Northern Hemisphere winter stratosphere and forcing of the 2 day wave in the Southern Hemisphere summer mesosphere. Variability of the planetary wave activity in the winter hemisphere may thus influence 2 day wave amplitudes in the summer hemisphere and further contribute to the observed interannual variability.

[70] The W4 was identified by *Salby and Callaghan* [2001b] as a Rossby-gravity (4, 0) mode. They presented a solstitial geopotential amplitude structure for this mode which suggests that in the summer mesosphere it reaches largest values from the tropics to middle/high latitudes at heights increasing from ~80 km in the tropics to ~90 km at higher latitudes. They suggested only limited penetration of this wave activity across the equator into the winter hemisphere. Our results (Figure 7) show that their model reproduces the gross features of the observed W4 structure (and actually show no evidence of significant penetration into the winter hemisphere). These similarities in structure between the modeled (4, 0) Rossby-gravity mode of *Salby and Callaghan* [2001b] and the observed W4 reported here provide strong support for the suggestion that the W4 is in fact a (4, 0) Rossby-gravity mode.

5. Conclusions

[71] EOS Aura MLS temperatures were analyzed from 2004 to 2009 in a latitude range of 70°N to 70°S. In both hemispheres, during the summer months, a large amplitude 2 day wave was observed with amplitudes reaching up to 12 K in the Southern Hemisphere. These large-amplitude summertime waves were then considered in more detail. A modeling study has shown that significant aliasing can occur between wave numbers associated with the 2 day wave. We have identified aliasing from an E2 high-latitude wave as something which can give rise to a spurious high-latitude W3 signal. Note that high-latitude E2 2 day waves have been reported in a numbers of studies [e.g., *Nozawa et al.*, 2003a; *Sandford et al.*, 2008] and so such aliasing could potentially be misleading.

[72] The data show that the summertime 2 day wave is a complex of wave numbers W2, W3 and W4 in both hemispheres. The W3 and W4 are the dominant wave numbers having the largest amplitudes throughout each summer compared with the W2 which has consistently smaller amplitudes.

[73] In the Southern Hemisphere the W3 amplitudes are largest and the 2 day wave is therefore dominated by the W3 component with amplitudes reaching up to about 11 K in 3 of the 5 summers observed. When the W3 reaches such large amplitudes it is reasonably short-lived, lasting only about one month. The W4 component does not reach amplitudes larger than 3 K during times of large W3 amplitudes making the 2 day wave predominantly a W3 wave during the summers of (2004/2005, 2005/2006, 2006/2007). During the summers of 2007/2008 and 2008/2009 the W3

reached amplitudes up to about 5 K only half that of the previous years. During this time the W4 had a similar amplitude making the resultant 2 day wave a mixture of W3 and W4 components. Despite the large degree of interannual variability in amplitudes, the structure of the waves in terms of height and latitude remains remarkably constant from year to year.

[74] In the Northern Hemisphere the 2 day wave is a mixture of W2, W3 and W4 waves. The W4 wave has larger amplitudes in this hemisphere and in 2006 was the largest amplitude of all the wave numbers, reaching amplitudes up to about 6 K.

[75] In both hemispheres the W4 appears to be a longer-lived wave and persists to have large amplitudes once the W3 has died away. This is apparent in most years observed.

[76] In this study we have found that the 2 day wave is nearly always a mixture of the W3 and W4 wave numbers rather than just a W3 wave and that the W4 appears to be the (4, 0) normal mode.

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References

Baumgaertner, A. J. G., A. J. McDonald, R. E. Hibbins, D. C. Fritts, D. J. Murphy, and R. A. Vincent (2008), Short-period planetary waves in the Antarctic middle atmosphere, *J. Atmos. Sol. Terr. Phys.*, *70*(10), 1336–1350, doi:10.1016/j.jastp.2008.04.007.

Clark, R. R., A. C. Current, A. H. Manson, C. E. Meek, S. K. Avery, S. E. Palo, and T. Aso (1994), Hemispheric properties of the 2 day wave from mesosphere lower-thermosphere radar observations, *J. Atmos. Terr. Phys.*, *56*(10), 1279–1288, doi:10.1016/0021-9169(94)90066-3.

Craig, R. L., R. A. Vincent, S. P. Kingsley, and H. G. Muller (1983), Simultaneous observations of the quasi 2 day wave in the northern and southern hemispheres, *J. Atmos. Terr. Phys.*, *45*(8–9), 539–541, doi:10.1016/S0021-9169(83)80068-3.

Forbes, J. M., and X. Zhang (1997), Quasi 2 day oscillation of the ionosphere: A statistical study, *J. Atmos. Sol. Terr. Phys.*, *59*(9), 1025–1034, doi:10.1016/S1364-6826(96)00175-7.

Forbes, J. M., R. Guffee, X. Zhang, D. Fritts, D. Riggin, A. Manson, C. Meek, and R. A. Vincent (1997), Quasi 2 day oscillation of the ionosphere during summer 1992, *J. Geophys. Res.*, *102*(A4), 7301–7305, doi:10.1029/96JA01744.

Garcia, R. R., R. Lieberman, J. M. Russell, and M. G. Mlynczak (2005), Large-Scale Waves in the Mesosphere and Lower Thermosphere Observed by SABER, *J. Atmos. Sci.*, *62*(12), 4384–4399, doi:10.1175/JAS3612.1.

Glass, M., J. L. Fellous, M. Massebeuf, A. Spizzichino, I. A. Lysenko, and Y. I. Portniaghin (1975), Comparison and interpretation of results of simultaneous wind measurements in lower thermosphere at Garchy (France) and Obninsk (U.S.S.R.) by meteor radar technique, *J. Atmos. Terr. Phys.*, *37*(8), 1077–1087, doi:10.1016/0021-9169(75)90153-1.

Gurubaran, S., S. Sridharan, T. K. Ramkumar, and R. Rajaram (2001), The mesospheric quasi-2 day wave over Tirunelveli (8.7°N), *J. Atmos. Sol. Terr. Phys.*, *63*(10), 975–985, doi:10.1016/S1364-6826(01)00016-5.

Harris, T. J., and R. A. Vincent (1993), The quasi-2 day wave observed in the equatorial middle atmosphere, *J. Geophys. Res.*, *98*(D6), 10,481–10,490, doi:10.1029/93JD00380.

Hecht, J. H., R. L. Walterscheid, L. J. Gelinas, R. A. Vincent, I. M. Reid, and J. M. Woithe (2010), Observations of the phase-locked 2 day wave over the Australian sector using medium-frequency radar and airglow data, *J. Geophys. Res.*, *115*, D16115, doi:10.1029/2009JD013772.

Jacobi, C., R. Schminder, and D. Kurschner (1997), The quasi 2 day wave as seen from D1 LF wind measurements over central Europe (52 °N, 15°E) at Collm, *J. Atmos. Sol. Terr. Phys.*, *59*(11), 1277–1286, doi:10.1016/S1364-6826(96)00170-8.

Jacobi, C., R. Schminder, and D. Kurschner (1998), Non-linear interaction of the quasi 2 day wave and longterm oscillations in the summer midlatitude mesopause region as seen from LF D1 wind measurements over Central Europe (Collm, 52°N, 15°E), *J. Atmos. Sol. Terr. Phys.*, *60*(12), 1175–1191, doi:10.1016/S1364-6826(98)00076-5.

Kulikov, M. Y. (2007), Theoretical investigation of the influence of a quasi-2-day wave on nonlinear photochemical oscillations in the mesopause region, *J. Geophys. Res.*, *112*, D02305, doi:10.1029/2005JD006845.

Li, T., C. Y. She, S. E. Palo, Q. Wu, H. L. Liu, and M. L. Salby (2008), Coordinated lidar and TIMED observations of the quasi-two-day wave during August 2002–2004 and possible quasi-biennial oscillation influence, *Adv. Space Res.*, *41*(9), 1463–1471, doi:10.1016/j.asr.2007.03.052.

Limpasuvan, V., and D. L. Wu (2003), Two-day wave observations of UARS Microwave Limb Sounder mesospheric water vapor and temperature, *J. Geophys. Res.*, *108*(D10), 4307, doi:10.1029/2002JD002903.

Limpasuvan, V., and D. L. Wu (2009), Anomalous two-day wave behavior during the 2006 austral summer, *Geophys. Res. Lett.*, *36*, L04807, doi:10.1029/2008GL036387.

Limpasuvan, V., C. B. Leovy, and Y. J. Orsolini (2000), Observed temperature two-day wave and its relatives near the stratopause, *J. Atmos. Sci.*, *57*(11), 1689–1701, doi:10.1175/1520-0469(2000)057<1689:OTTDWA>2.0.CO;2.

Limpasuvan, V., D. L. Wu, M. J. Schwartz, J. W. Waters, Q. Wu, and T. L. Killeen (2005), The two-day wave in EOS MLS temperature and wind measurements during 2004–2005 winter, *Geophys. Res. Lett.*, *32*, L17809, doi:10.1029/2005GL023396.

Livesey, N. J., W. Van Snyder, W. G. Read, and P. A. Wagner (2006), Retrieval Algorithms for the EOS Microwave Limb Sounder (MLS), *IEEE Trans. Geosci. Remote Sens.*, *44*(5), 1144–1155, doi:10.1109/TGRS.2006.872327.

Livesey, N. J., et al. (2007), Version 2.2 level 2 data quality and description document, Version 2.2 D-33509, pp. 91,109–98,099, Jet Propul. Lab., Calif. Inst. of Technol., Pasadena, Calif.

Manson, A. H., et al. (2004a), Longitudinal and latitudinal variations in dynamic characteristics of the MLT (70–95 km): A study involving the CUJO network, *Ann. Geophys.*, *22*(2), 347–365, doi:10.5194/angeo-22-347-2004.

Manson, A. H., C. E. Meek, C. M. Hall, S. Nozawa, N. J. Mitchell, D. Pancheva, W. Singer, and P. Hoffmann (2004b), Mesopause dynamics from the scandinavian triangle of radars within the PSMOS-DATAR Project, *Ann. Geophys.*, *22*(2), 367–386, doi:10.5194/angeo-22-367-2004.

McCormack, J. P., L. Coy, and K. W. Hoppel (2009), Evolution of the quasi 2-day wave during January 2006, *J. Geophys. Res.*, *114*, D20115, doi:10.1029/2009JD012239.

McCormack, J. P., S. D. Eckermann, K. W. Hoppel, and R. A. Vincent (2010), Amplification of the quasi-two day wave through nonlinear interaction with the migrating diurnal tide, *Geophys. Res. Lett.*, *37*, L16810, doi:10.1029/2010GL043906.

Meek, C. E., and A. H. Manson (2009), Summer planetary-scale oscillations: Aura MLS temperature compared with ground-based radar wind, *Ann. Geophys.*, *27*(4), 1763–1774, doi:10.5194/angeo-27-1763-2009.

Merkel, A. W., D. W. Rusch, S. E. Palo, J. M. Russell, and S. M. Bailey (2009), Mesospheric planetary wave effects on global PMC variability inferred from AIM-CIPS and TIMED-SABER for the northern summer 2007 PMC season, *J. Atmos. Sol. Terr. Phys.*, *71*(3–4), 381–391, doi:10.1016/j.jastp.2008.12.001.

Merzlyakov, E., D. Pancheva, N. Mitchell, J. M. Forbes, Y. I. Portnyagin, S. Palo, N. Makarov, and H. G. Muller (2004), High- and mid-latitude quasi-2 day waves observed simultaneously by four meteor radars during summer 2000, *Ann. Geophys.*, *22*(3), 773–788, doi:10.5194/angeo-22-773-2004.

Mitchell, N. J., P. J. S. Williams, A. G. Beard, G. R. Buesnel, and H. G. Muller (1996), Non-linear planetary tidal wave interactions in the lower thermosphere observed by meteor radar, *Ann. Geophys.*, *14*(3), 364–366.

Morris, R. J., A. R. Klekociuk, and D. A. Holdsworth (2009), Low latitude 2-day planetary wave impact on austral polar mesopause temperatures: Revealed by a January diminution in PMSE above Davis, Antarctica, *Geophys. Res. Lett.*, *36*, L11807, doi:10.1029/2009GL037817.

Muller, H. G. (1972), Long-period meteor wind oscillations, *Philos. Trans. R. Soc. London, Ser. A*, *271*, 585–599, doi:10.1098/rsta.1972.0026.

Muller, H. G., and L. Nelson (1978), Traveling quasi 2 day wave in meteor region, *J. Atmos. Terr. Phys.*, *40*(6), 761–766, doi:10.1016/0021-9169(78)90136-8.

Norton, W. A., and J. Thuburn (1996), The two-day wave in a middle atmosphere GCM, *Geophys. Res. Lett.*, *23*(16), 2113–2116, doi:10.1029/96GL01956.

Nozawa, S., S. Imaida, A. Brekke, C. M. Hall, A. Manson, C. Meek, S. Oyama, K. Dobashi, and R. Fujii (2003a), The quasi 2-day wave observed in the polar mesosphere, *J. Geophys. Res.*, *108*(D2), 4039, doi:10.1029/2002JD002440.

Nozawa, S., H. Iwahashi, A. Brekke, C. M. Hall, C. Meek, A. Manson, S. Oyama, Y. Murayama, and R. Fujii (2003b), The quasi 2-day wave observed in the polar mesosphere: Comparison of the characteristics observed at Tromsøand Poker Flat, *J. Geophys. Res.*, *108*(D24), 4748, doi:10.1029/2002JD003221.

Nozawa, S., et al. (2005), Mean winds, tides, and quasi-2 day wave in the polar lower thermosphere observed in European Incoherent Scatter (EISCAT) 8 day run data in November 2003, *J. Geophys. Res.*, *110*, A12309, doi:10.1029/2005JA011128.

Offermann, D., P. Hoffmann, P. Knieling, R. Koppmann, J. Oberheide, D. M. Riggin, V. M. Tunbridge, and W. Steinbrecht (2011), Quasi 2 day waves in the summer mesosphere: Triple structure of amplitudes and long-term development, *J. Geophys. Res.*, *116*, D00P02, doi:10.1029/2010JD015051.

Palo, S. E., and S. K. Avery (1996), Observations of the quasi-two-day wave in the middle and lower atmosphere over Christmas Island, *J. Geophys. Res.*, *101*(D8), 12,833–12,846, doi:10.1029/96JD00699.

Palo, S. E., R. G. Roble, and M. E. Hagan (1999), Middle atmosphere effects of the quasi-two-day wave determined from a general circulation model, *Earth Planets Space*, *51*(7–8), 629–647.

Palo, S. E., J. M. Forbes, X. Zhang, J. M. Russell, and M. G. Mlynczak (2007), An eastward propagating two-day wave: Evidence for nonlinear planetary wave and tidal coupling in the mesosphere and lower thermosphere, *Geophys. Res. Lett.*, *34*(7), L07807, doi:10.1029/2006GL027728.

Pancheva, D., et al. (2004), Variability of the quasi-2 day wave observed in the MLT region during the PSMOS campaign of June–August 1999, *J. Atmos. Sol. Terr. Phys.*, *66*(6–9), 539–565, doi:10.1016/j.jastp.2004.01.008.

Pfister, L. (1985), Baroclinic instability of easterly jets with applications to the summer mesosphere, *J. Atmos. Sci.*, *42*(4), 313–330, doi:10.1175/1520-0469(1985)042<0313:BIOEJW>2.0.CO;2.

Plumb, R. A. (1983), Baroclinic instability of the summer mesosphere—A mechanism for the quasi-2 day wave, *J. Atmos. Sci.*, *40*(1), 262–270, doi:10.1175/1520-0469(1983)040<0262:BIOTSM>2.0.CO;2.

Plumb, R. A., R. A. Vincent, and R. L. Craig (1987), The quasi-2 day wave event of January 1984 and its impact on the mean mesospheric circulation, *J. Atmos. Sci.*, *44*(20), 3030–3036, doi:10.1175/1520-0469(1987)044<3030:TQTDWE>2.0.CO;2.

Riggin, D. M., R. S. Lieberman, R. A. Vincent, A. H. Manson, C. E. Meek, T. Nakamura, T. Tsuda, and Y. I. Portnyagin (2004), The 2-day wave during the boreal summer of 1994, *J. Geophys. Res.*, *109*, D08110, doi:10.1029/2003JD004493.

Rodgers, C. D., and A. J. Prata (1981), Evidence for a traveling 2 day wave in the middle atmosphere, *J. Geophys. Res.*, *86*(C10), 9661–9664, doi:10.1029/JC086iC10p09661.

Rojas, M., and W. Norton (2007), Amplification of the 2-day wave from mutual interaction of global Rossby-gravity and local modes in the summer mesosphere, *J. Geophys. Res.*, *112*, D12114, doi:10.1029/2006JD008084.

Salby, M. L. (1982a), Sampling theory for asynoptic satellite-observations. 1. space-time spectra, resolution, and aliasing, *J. Atmos. Sci.*, *39*(11), 2577–2600, doi:10.1175/1520-0469(1982)039<2577:STFASO>2.0.CO;2.

Salby, M. L. (1982b), Sampling theory for asynoptic satellite-observations. 2. fast fourier synoptic mapping, *J. Atmos. Sci.*, *39*(11), 2601–2614, doi:10.1175/1520-0469(1982)039<2601:STFASO>2.0.CO;2.

Salby, M. L., and P. F. Callaghan (2001a), Seasonal amplification of the 2 day wave: Relationship between normal mode and instability, *J. Atmos. Sci.*, *58*(14), 1858–1869, doi:10.1175/1520-0469(2001)058<1858:SAOTDW>2.0.CO;2.

Salby, M. L., and P. F. Callaghan (2001b), Seasonal amplification of the 2 day wave: Relationship between normal mode and instability, *J. Atmos. Sci.*, *58*(14), 1858–1869, doi:10.1175/1520-0469(2001)058<1858:SAOTDW>2.0.CO;2.

Salby, M. L., and P. F. Callaghan (2008), Interaction of the 2-day wave with solar tides, *J. Geophys. Res.*, *113*, D14121, doi:10.1029/2006JD007892.

Salby, M. L., and R. G. Roper (1980), Long-period oscillations in the meteor region, *J. Atmos. Sci.*, *37*(1), 237–244, doi:10.1175/1520-0469(1980)037<0237:LPOITM>2.0.CO;2.

Sandford, D. J., M. J. Schwartz, and N. J. Mitchell (2008), The wintertime two-day wave in the polar stratosphere, mesosphere and lower thermosphere, *Atmos. Chem. Phys.*, *8*(3), 749–755, doi:10.5194/acp-8-749-2008.

Schwartz, M. J., et al. (2008), Validation of the Aura Microwave Limb Sounder temperature and geopotential height measurements, *J. Geophys. Res.*, *113*, D15S11, doi:10.1029/2007JD008783.

Teitelbaum, H., and F. Vial (1991), On tidal variability induced by nonlinear interaction with planeatry waves, *J. Geophys. Res.*, *96*(A8), 14,169–14,178, doi:10.1029/91JA01019.

Thayaparan, T., W. K. Hocking, and J. MacDougall (1997), Amplitude, phase, and period variations of the quasi 2 day wave in the mesosphere and lower thermosphere over London, Canada (43°N, 81°W), during 1993 and 1994, *J. Geophys. Res.*, *102*(D8), 9461–9478, doi:10.1029/96JD03869.

Tsuda, T., S. Kato, and R. A. Vincent (1988), Long period wind oscillations observed by the Kyoto meteor radar and comparison of the quasi-2 day wave with Adelaide HF radar observations, *J. Atmos. Terr. Phys.*, *50*(3), 225–230, doi:10.1016/0021-9169(88)90071-2.

Tunbridge, V. M., and N. J. Mitchell (2009), The two-day wave in the Antarctic and Arctic mesosphere and lower thermosphere, *Atmos. Chem. Phys.*, *9*(17), 6377–6388, doi:10.5194/acp-9-6377-2009.

Walterscheid, R. L., and R. A. Vincent (1996), Tidal generation of the phase-locked 2 day wave in the southern hemisphere summer by wave-wave interactions, *J. Geophys. Res.*, *101*(D21), 26,567–26,576, doi:10.1029/96JD02248.

Ward, W. E., D. Y. Wang, B. H. Solheim, and G. G. Shepherd (1996), Observations of the two-day wave in WINDII data during January, 1993, *Geophys. Res. Lett.*, *23*(21), 2923–2926, doi:10.1029/96GL02897.

Waters, J. W., et al. (2006), The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura Satellite, *IEEE Trans. Geosci. Remote Sens.*, *44*(5), 1075–1092, doi:10.1109/TGRS.2006.873771.

Wu, D. L., P. B. Hays, W. R. Skinner, A. R. Marshall, M. D. Burrage, R. S. Lieberman, and D. A. Ortland (1993), Observations of the quasi 2 day wave from the High-Resolution Doppler Imager on UARS, *Geophys. Res. Lett.*, *20*(24), 2853–2856, doi:10.1029/93GL03008.

Wu, D. L., P. Hays, and W. Skinner (1995), A least-squares method for spectral-analysis of space-time series, *J. Atmos. Sci.*, *52*(20), 3501–3511, doi:10.1175/1520-0469(1995)052<3501:ALSMFS>2.0.CO;2.

Wu, D. L., M. J. Schwartz, J. W. Waters, V. Limpasuvan, Q. A. Wu, and T. L. Killeen (2008), Mesospheric doppler wind measurements from Aura Microwave Limb Sounder (MLS), *Adv. Space Res.*, *42*(7), 1246–1252, doi:10.1016/j.asr.2007.06.014.

Yamada, Y. (2009), Horizontal structure of the geomagnetic 2 day variation, *J. Geophys. Res.*, *114*, A12312, doi:10.1029/2009JA014307.

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